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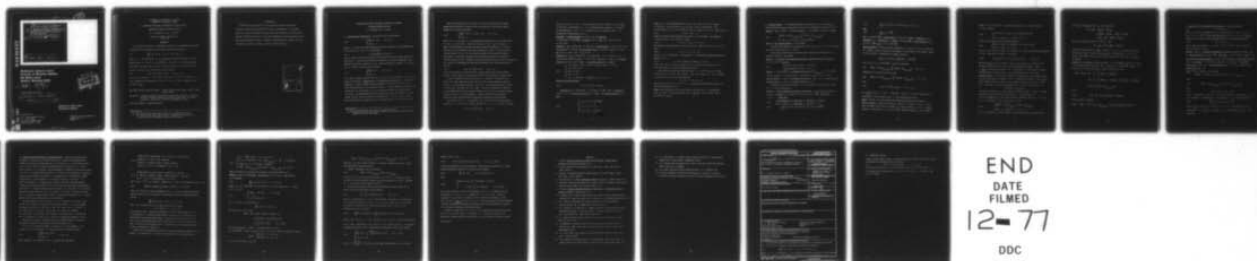
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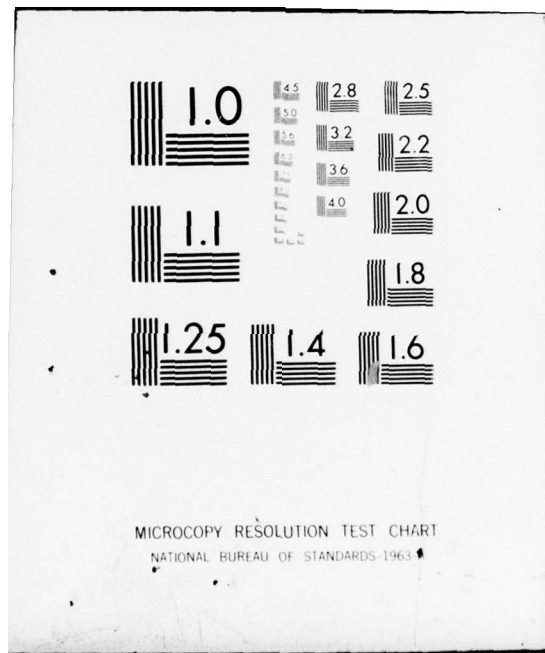
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MRC Technical Summary Report #1765

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VOLTERRA EQUATION.

M. G. Crandall J. A. Nohel

MRC-TSR-1765

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Jul 1977

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(Received May 16, 1977)

DAAG 29-75-C-0024
DAAG 29-77-C-0004

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AN ABSTRACT FUNCTIONAL DIFFERENTIAL EQUATION AND A

RELATED NONLINEAR VOLTERRA EQUATION

M. G. Crandall¹ and J. A. Nohel²

Technical Summary Report #1765
July 1977

ABSTRACT

We study the existence, uniqueness, regularity and dependence upon data of solutions of the abstract functional differential equation

$$(1) \quad \frac{du}{dt} + Au \ni G(u) \quad (0 \leq t \leq T), \quad u(0) = x,$$

where $T > 0$ is arbitrary, A is a given m -accretive operator in a real Banach space X , and $G : C([0, T]; \overline{D(A)}) \rightarrow L^1(0, T; X)$ is a given mapping. This study provides simple proofs of generalizations of results by several authors concerning the nonlinear Volterra equation

$$(2) \quad u(t) + b * Au(t) \ni F(t) \quad (0 \leq t \leq T),$$

for the case in which X is a real Hilbert space. In (2) the kernel b is real, absolutely continuous on $[0, T]$, $b * g(t) = \int_0^t b(t-s)g(s)ds$, and $F \in W^{1,1}(0, T; X)$.

AMS (MOS) Subject Classifications: 47H15, 34K05, 45N05, 34G05, 47H10, 47H05, 47H99, 47G05

Key Words: nonlinear abstract functional differential equations, nonlinear abstract Volterra equations, evolution equations, m -accretive operators, regularity, continuous dependence on data

Work Unit Number 1 (Applied Analysis)

Sponsored by:

- 1) The United States Army under Contract No. DAAG29-75-C-0024;
- 2) The United States Army under Grant No. DAAG29-77-G-0004 and the National Science Foundation Grant No. MCS75-21868.

EXPLANATION

An "m-accretive operator" is an abstraction which covers many nonlinear differential operators arising in applications. This paper shows how certain problems involving evolution equations with m-accretive operators and delay effects in the time dependence can be discussed within the existing abstract theory. Indeed, a (theoretically) simple iterative procedure is shown to converge to the desired solution.

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AN ABSTRACT FUNCTIONAL DIFFERENTIAL EQUATION AND A RELATED

NONLINEAR VOLTERRA EQUATION

M. G. Crandall¹ and J. A. Nohel²

1. Introduction and Preliminaries. We study the initial value problem

$$(1.1) \quad \begin{cases} \frac{du}{dt} + Au \ni G(u) & (0 \leq t \leq T), \\ u(0) = x \end{cases}$$

where A is a given m -accretive (possibly multi-valued) operator in a real Banach space X with norm $\|\cdot\|$, and G is a given mapping

$$(1.2) \quad G : C([0, T]; \overline{D(A)}) \rightarrow L^1(0, T; X).$$

(See [1] and [8] concerning the notion of an m -accretive operator and other notation not defined here.) Points of interest will be the existence, uniqueness, regularity, and dependence upon data of solutions of (1.1). The method employed is simple. If $x \in \overline{D(A)}$ and $g \in L^1(0, T; X)$, then the evolution problem

$$(1.3) \quad \begin{cases} \frac{dv}{dt} + Av \ni g & (0 \leq t \leq T), \\ v(0) = x \end{cases}$$

has a unique "integral" solution (see [1], [5], or [8]) $v \in C([0, T]; \overline{D(A)})$. Let $v = H(g)$ denote this solution. A solution of (1.1) is by definition a function $u \in C([0, T]; \overline{D(A)})$ such that $u = H(G(u))$. Under suitable assumptions, some iterate of $K = H(G)$ is a strict contraction and (1.1) has a unique solution u . Further assumptions allow stronger conclusions, e.g. the solution of (1.1) is Lipschitz continuous or a strong solution (see below). The method adapts easily to generalizations (e.g., the operator $A = A(t)$ depends on time), and to the study of the dependence of u on A , G , and x . The basic idea used here is already found in [5] and exploited for G as in (1.2) in [9].

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- 1) The United States Army under Contract No. DAAG29-75-C-0024;
- 2) The United States Army under Grant No. DAAG29-77-G-0004 and the National Science Foundation Grant No. MCS75-21868.

Much of the motivation for our study of (1.1) lies in the fact that we thereby obtain very simple proofs of generalization of results due to several other authors. MacCamy [15] considers the problem

$$(1.4) \quad \begin{cases} \frac{du}{dt} + mA(t) + a * Au(t) = f(t) & (0 < t \leq T), \\ u(0) = x \end{cases}$$

where $m > 0$ is a constant, A is a maximal monotone operator in a real Hilbert space H , and a is a real kernel. We use the notation $a * g(t) = \int_0^t a(t-s)g(s)ds$. Under various additional restrictions, MacCamy transforms the problem (1.4) to one of the form (1.1) by the method of the proof of Proposition 1 below. He then treats the resulting special case of (1.1) via a Galerkin argument (which necessitates further restrictions). Our results concerning (1.1) are directly applicable to problems of the sort discussed in [15]. Moreover, we also obtain generalizations of results of Barbu [2], [3], Londen [13], Gripenberg [11] and Londen and Staffans [14] concerning equations of the form

$$(1.5) \quad u(t) + b * Au(t) = F(t) \quad (0 \leq t \leq T).$$

The Volterra equation (1.5) was treated in a Hilbert space setting by these authors, whereas we obtain results in general Banach spaces by very different and simpler proofs.

Section 2 contains the basic results for (1.1). Applied to the study of (1.5) these results show, among other things, that (1.5) has a unique generalized solution whenever b is absolutely continuous, $b(0) > 0$, b' is of bounded variation on $[0, T]$, $F \in W^{1,1}(0, T; X)$ (see below) and $F(0) \in \overline{D(A)}$. This fact is established in Section 3, but we present below the basic connection between (1.1) and (1.5) in the case of strong solutions (which will be defined shortly). Section 4 sketches the relationship between this paper and the existing literature and outlines some generalizations.

First recall that if I is an interval, then $u \in W^{1,1}(I; X)$ means that there is a function $v : I \rightarrow X$ which is strongly integrable on I (i.e. $v \in L^1(I; X)$) such that

$$u(t) - u(s) = \int_s^t v(\tau) d\tau \quad (t, s \in I);$$

then $u'(t) = v(t)$ a.e. on I . It is also known (e.g. [6, p. 148] or [1, p. 16]) that $u \in W^{1,1}(I;X)$ is equivalent to $u : I \rightarrow X$ being absolutely continuous ($u \in AC(I;X)$) and differentiable a.e. on I . If $u \in AC(I;X)$ and X is reflexive, then u is automatically differentiable a.e. on I .

Definition. A strong solution of (1.1) on $[0,T]$ is a function $u \in W^{1,1}(0,T;X) \cap C([0,T];\overline{D(A)})$ satisfying $u(0) = x$ and $u'(t) + Au(t) = G(u)(t)$ a.e. on $[0,T]$.

Definition. Let $b \in L^1(0,T;\mathbb{R})$, $F \in L^1(0,T;X)$. A strong solution u of (1.5) on $[0,T]$ is a function $u \in L^1(0,T;X)$ for which there exists $w \in L^1(0,T;X)$ with $w(t) \in Au(t)$ and $u(t) + b * w(t) = F(t)$ a.e. on $[0,T]$.

Proposition 1. Let $b \in AC([0,T];\mathbb{R})$, $b' \in BV([0,T];\mathbb{R})$ (i.e. $b':[0,T] \rightarrow \mathbb{R}$ is of essentially bounded variation), $F \in W^{1,1}(0,T;X)$ and $b(0) = 1$. Let u be a strong solution of (1.5) on $[0,T]$. Then u is a strong solution of (1.1) where

$$(1.6) \quad \begin{cases} (i) & G(u)(t) = f(t) + r * f(t) - r(0)u(t) + r(t)x - u * r'(t) , \\ (ii) & f(t) = F'(t) , \\ (iii) & x = F(0) , \\ (iv) & a = b' , \\ (v) & r \in L^1(0,T;\mathbb{R}) \text{ is defined by } r + a * r = -a , \end{cases}$$

and we have used the notation

$$(1.7) \quad u * r'(t) = \int_0^t u(t-s)dr(s) .$$

Conversely, let $r \in BV([0,T];\mathbb{R})$, $f \in L^1(0,T;X)$, $x \in \overline{D(A)}$, and G be given by (1.6(i)). If u is a strong solution of (1.1), then u is a strong solution of (1.5), where

$$(1.8) \quad \begin{cases} (i) & F(t) = x + \int_0^t f(s)ds , \\ (ii) & a + a * r = -r , \\ (iii) & b(t) = 1 + \int_0^t a(s)ds . \end{cases}$$

Proof: Let u be a strong solution of (1.5) on $[0, T]$ and $u + b * w = F$ where $w \in L^1(0, T; X)$, and $w(t) \in Au(t)$ a.e. on $[0, T]$. Since $b \in AC([0, T]; \mathbb{R})$ and $F \in W^{1,1}(0, T; X)$, $u = F - b * w \in W^{1,1}(0, T; X)$ and $u' + b(0)w + b' * w = F'$. Since $b(0) = 1$,

$$(1.9) \quad w + b' * w = F' - u'.$$

Simple facts about Volterra equations imply that if $r, a \in L^1(0, T; \mathbb{R})$ are related via (1.6(iv)), then for $v, w \in L^1(0, T; X)$ we have

$$(1.10) \quad w + a * w = v \iff v + r * v = w.$$

The reader can easily check this (or see [16, Chp. 4]). Hence (1.9) and $r + b' * r = -b'$ imply

$$(1.11) \quad w = F' - u' + r * (F' - u').$$

Finally, $a = b' \in BV([0, T]; \mathbb{R})$ is equivalent to $r \in BV([0, T]; \mathbb{R})$ (Bellman and Cooke [4; Theorem 7.4]), so

$$(1.12) \quad r * u'(t) = r(0)u(t) - r(t)u(0) + u * r'(t).$$

Since $u(0) = F(0) = x$ and $w(t) \in Au(t)$ a.e., (1.11) and (1.12) show that u is a strong solution of (1.1) with the identifications (1.6).

The converse is proved by reversing the steps. If $u \in W^{1,1}(0, T; X)$ is a strong solution of (1.1) on $[0, T]$, then $G(u)(t) - u'(t) = w(t) \in Au(t)$ a.e. If G is given by (1.6(i)) and (1.12) is used, one finds that

$$(f - u') + r * (f - u') = w,$$

and by using (1.10) that $w + a * w = f - u'$. Integration of this equation yields (1.5) with the identifications (1.8).

Remark. When considering (1.5) one may reduce to the case $b(0) = 1$, provided that $b(0) > 0$, since A may be replaced by $b(0)A$. Formally, $b * Au = \tilde{b} * \tilde{A}u$, where $\tilde{b} = b(0)^{-1}b$, $\tilde{A} = b(0)A$.

2. Principal Results. It is assumed throughout this section that A is m -accretive.

The following simple result establishes the existence and uniqueness of solutions of (1.1).

Theorem 1. Let $x \in \overline{D(A)}$, $\gamma \in L^1(0, T; \mathbb{R})$ and let $G : C([0, T]; \overline{D(A)}) \rightarrow L^1(0, T; X)$ satisfy

$$(2.1) \quad \begin{cases} \|G(u) - G(v)\|_{L^1(0, t; X)} \leq \int_0^t \gamma(s) \|u - v\|_{L^\infty(0, s; X)} ds \\ \text{for } 0 \leq t \leq T \text{ and } u, v \in C([0, T]; \overline{D(A)}) . \end{cases}$$

Then (1.1) has a unique solution $u \in C([0, T]; \overline{D(A)})$.

We remark that assumption (2.1) implies that the value of $G(u)$ at $t \in [0, T]$ depends only on the restriction of u to $[0, t]$.

Under further assumptions one can obtain greater regularity of solutions of (1.1) than mere continuity. For example:

Theorem 2. In addition to the hypotheses of Theorem 1 assume that there is a function $k : [0, \infty) \rightarrow [0, \infty)$ such that

$$(2.2) \quad \begin{cases} \text{var}(G(u) : [0, t]) \leq k(R) (1 + \text{var}(u : [0, t])) \\ \text{and } \|G(u)(0+)\| \leq k(R), \quad 0 \leq t \leq T, \end{cases}$$

whenever $u \in C([0, T]; \overline{D(A)})$ is of bounded variation and $\|u\|_{L^\infty(0, T; X)} \leq R$. (The varia-

tion of a function v over an interval I is denoted by $\text{var}(v; I)$.) If $x \in D(A)$,

then the solution u of (1.1) is Lipschitz continuous on $[0, T]$. If X is also reflexive,

then the solution u of (1.1) is a strong solution on $[0, T]$.

Finally, we note that the solution u of (1.1) depends continuously on the "data"

A, G, x in the following sense:

Theorem 3. Let the assumptions of Theorem 1 be satisfied. Let an m -accretive operator

A_n in X , a mapping $G_n : C([0, T]; X) \rightarrow L^1(0, T; X)$ and $x_n \in \overline{D(A_n)}$ be given for $n = 1, 2, \dots$. Assume that:

$$(2.3) \quad \begin{cases} \text{The inequality (2.1) holds with } G \text{ replaced by } G_n \text{ for all} \\ u, v \in C([0, T]; X), \text{ with the same } \gamma \text{ for each } n = 1, 2, \dots; \end{cases}$$

$$(2.4) \quad \lim_{n \rightarrow \infty} G_n(u) = G(u) \text{ in } L^1(0, T; X) \text{ for } u \in C([0, T]; \overline{D(A)}) ;$$

$$(2.5) \quad \lim_{n \rightarrow \infty} (I + \lambda A_n)^{-1} z = (I + \lambda A)^{-1} z \quad \text{for } \lambda > 0, z \in X;$$

and

$$(2.6) \quad \lim_{n \rightarrow \infty} x_n = x \in \overline{D(A)}.$$

Let $u_n \in C([0, T]; \overline{D(A_n)})$ be solutions of (1.1) on $[0, T]$ with A replaced by A_n , G replaced by G_n , x replaced by x_n and let $u \in C([0, T]; \overline{D(A)})$ be the solution of (1.1) on $[0, T]$. Then $\lim_{n \rightarrow \infty} u_n = u$ in $C([0, T]; X)$.

Proof of Theorem 1: Denote the integral solution of $v' + Av = g$, $v(0) = x$, $g \in L^1(0, T; X)$ by $v = H(g)$. We seek a fixed point of the map $K : C([0, T]; \overline{D(A)}) \rightarrow C([0, T]; \overline{D(A)})$ defined by $K(u) = H(G(u))$. By properties of integral solutions

$$\|K(u)(t) - K(v)(t)\| \leq \int_0^t \|G(u)(s) - G(v)(s)\| ds$$

for $0 \leq t \leq T$, $u, v \in C([0, T]; \overline{D(A)})$. By (2.1) we thus have

$$(2.7) \quad \|K(u) - K(v)\|_{L^\infty(0, t; X)} \leq \int_0^t \gamma(s) \|u - v\|_{L^\infty(0, s; X)} ds \quad (0 \leq t \leq T).$$

Iterating (2.7) one shows by induction that

$$(2.8) \quad \|K^j(u) - K^j(v)\|_{L^\infty(0, t; X)} \leq \int_0^t \gamma_j(s) \|u - v\|_{L^\infty(0, s; X)} ds \quad (0 \leq t \leq T)$$

where

$$(2.9) \quad \gamma_j(s) = \gamma(s) \int_0^s \gamma_{j-1}(\sigma) d\sigma; \quad j = 2, 3, \dots; \gamma_1 = \gamma.$$

Now $\lim_{j \rightarrow \infty} \int_0^T \gamma_j(s) ds = 0$, since $\gamma \in L^1(0, T; \mathbb{R})$, and so K^j is a strict contraction on $C([0, T]; \overline{D(A)})$ for sufficiently large j . This establishes the result.

Remark: Theorem 1 is a mild generalization (with the same proof) of [9; Lemma 2.1].

Proof of Theorem 2: Define the function $u_0 : [0, T] \rightarrow X$ by $u_0(t) = x$, $0 \leq t \leq T$. The proof of Theorem 1 shows that the iterates $u_{n+1} = K(u_n) = H(G(u_n))$, $n = 0, 1, \dots$, converge uniformly to the solution u of (1.1) on $[0, T]$. Hence the iterates u_n are uniformly

bounded. If $g \in BV([0, T]; X)$ in the evolution equation (1.3), then the solution $v = H(g)$ satisfies

$$(2.10) \quad \begin{cases} \text{var}(v; [0, t]) \leq \|g(0+) - y\| t + \int_0^t \text{var}(g; [0, \tau]) d\tau \\ \text{for } y \in Av(0) = Ax \text{ and for } 0 \leq t \leq T. \end{cases}$$

In fact (2.10) follows from the stronger inequality

$$(2.11) \quad \begin{cases} \|v(\xi) - v(\eta)\| \leq |\xi - \eta| [\|g(0+) - y\| + \text{var}(g; [0, t])] \\ \text{for } y \in Av(0), \quad 0 \leq \xi, \eta \leq t. \end{cases}$$

See, e.g. [1, p. 132] or [5, Prop. 1.6]. Thus by (2.2), (2.10) and the uniform boundedness of $\{u_n\}$, there exists a constant c such that

$$(2.12) \quad \text{var}(u_{n+1}; [0, t]) \leq c(1 + \int_0^t \text{var}(u_n; [0, \tau]) d\tau) \quad (0 \leq t \leq T).$$

But then $\text{var}(u_{n+1}; [0, t]) \leq c \exp(ct)$. Thus $\{\text{var}(u_n; [0, T])\}$ and $\text{var}(G(u_n); [0, T])$ are both bounded. By (2.11), $\{u_n\}$ is uniformly Lipschitz continuous. Hence $u = \lim_{n \rightarrow \infty} u_n$ is Lipschitz continuous. If X is reflexive, $u \in W^{1,1}([0, T]; X)$ follows from the absolute continuity, and u is a strong solution of (1.1) on $[0, T]$.

Proof of Theorem 3: In the proof of Theorem 1 the solution of (1.1) was represented as the unique fixed point of a mapping $K = HG$. H depends on the "data" A and x which we now exhibit explicitly: $H(A, x, g)$ is the integral solution of (1.3) for $x \in \overline{D(A)}$ and $g \in L^1(0, T; X)$. We indicate the dependence of K on A, x, G of (1.1) by

$$K(A, \gamma, G)(u) = H(A, x, G(u)).$$

In the proof of Theorem 1, K^j was a strict contraction for some j . Both j and the contraction constant depend only on the function γ which we assume in

(2.3) to be uniform in n . Thus, by the argument of Theorem 1, there is a $j > 0$ and $0 < \ell < 1$ such that if $K_n(u) = K(A_n, x_n, G_n)(u)$, then

$$(2.13) \quad \begin{cases} \|K_n^j(u) - K_n^j(v)\|_{L^\infty(0, T; X)} \leq \ell \|u - v\|_{L^\infty(0, T; X)} \\ \text{for } u, v \in C([0, T]; X), \quad n = 1, 2, \dots \end{cases}$$

If $u \in C([0, T]; \overline{D(A)})$, $u_n \in C([0, T]; \overline{D(A_n)})$ satisfy the equations $K(u) = K(A, x, G)(u) = u$

and $K_n(u_n) = K(A_n, x_n, G_n)(u_n) = u_n$, then using (2.13)

$$\begin{aligned} \|u - u_n\|_\infty &= \|K_n^j(u_n) - K^j(u)\|_\infty \\ &\leq \|K_n^j(u_n) - K_n^j(u)\|_\infty + \|K_n^j(u) - K^j(u)\|_\infty \\ &\leq \ell \|u_n - u\|_\infty + \|K_n^j(u) - K^j(u)\|_\infty, \end{aligned}$$

where $\|\cdot\|_\infty$ denotes the norm in $L^\infty(0, T; X)$. Thus

$$\|u - u_n\|_\infty \leq \frac{1}{1 - \ell} \|K_n^j(u) - K^j(u)\|_\infty,$$

and the assertion follows if $\|K_n^j(u) - K^j(u)\|_\infty \rightarrow 0$ as $n \rightarrow \infty$. For this it suffices

to know that $\|K_n(u) - K(u)\|_\infty = \|H(A_n, x_n, G_n)(u) - H(A, x, G)(u)\|_\infty \rightarrow 0$ as $n \rightarrow \infty$.

But the latter follows from [5, Prop. 1.23] in view of (2.4), (2.5), (2.6). The proof is complete.

Remark 2.14: The dependence of the fixed point u of the mapping $K(A, x, G)$ on x and G can be exhibited more precisely. Let $u = K(A, x, G)(u)$, $\hat{u} = K(A, \hat{x}, \hat{G})(\hat{u})$ where G, \hat{G} satisfy (2.1). Then by properties of integral solutions and (2.1)

$$\begin{aligned} \|\hat{u}(t) - u(t)\| &\leq \|x - \hat{x}\| + \int_0^t \|G(u)(s) - \hat{G}(\hat{u})(s)\| ds \\ &\leq \|x - \hat{x}\| + \int_0^t \|G(u)(s) - G(\hat{u})(s)\| ds + \int_0^t \|G(\hat{u})(s) - \hat{G}(\hat{u})(s)\| ds \\ &\leq e(t) + \int_0^t \gamma(s) \|u - \hat{u}\|_{L^\infty(0, s; X)} ds, \end{aligned}$$

where

$$(2.15) \quad e(t) = \|x - \hat{x}\| + \int_0^t \|G(\hat{u})(s) - \hat{G}(\hat{u})(s)\| ds.$$

Thus by Gronwall's inequality

$$(2.16) \quad \|\hat{u}(t) - u(t)\| \leq \|\hat{u} - u\|_{L^\infty(0, t; X)} \leq e(t) + \int_0^t \exp\left(\int_s^t \gamma(\tau) d\tau\right) e(s) ds.$$

3. Applications to the Abstract Volterra Equation. Consider the problem

$$(3.1) \quad u + b * Au \ni F,$$

where b, F are as in Proposition 1 and A is m -accretive on X . Let $\lambda > 0$ and $A_\lambda = \lambda^{-1}(I - (I + \lambda A)^{-1})$ be the Yosida approximation of A . $A_\lambda : X \rightarrow X$ is Lipschitz continuous, so a simple contraction argument shows that the approximating problem

$$(3.1)_\lambda \quad u_\lambda + b * A_\lambda u_\lambda = F$$

has a unique strong solution u_λ on $[0, T]$ if $b \in L^1(0, T; \mathbb{R})$ and $F \in L^1(0, T; X)$.

Our main result for (3.1) is:

Theorem 4. Let b, F satisfy the assumptions of Proposition 1 and $F(0) \in \overline{D(A)}$. Let u_λ be the solution of (3.1) $_\lambda$ on $[0, T]$. Then $\lim_{\lambda \rightarrow 0} u_\lambda = u$ in $C([0, T]; X)$ where u is the solution of the delay equation (1.1) on $[0, T]$ of Theorem 1, with the identifications (1.6). If, moreover, $F' \in BV([0, T]; X)$ and $F(0) \in D(A)$, then u is Lipschitz continuous on $[0, T]$. If X is also reflexive, then $u \in W^{1,1}(0, T; X)$ and u is a strong solution of (3.1).

Proof: With G given by (1.6)(i) we have

$$\|G(u)(t) - G(v)(t)\| \leq (|r(0)| + \text{var}(r: [0, t])) \|u - v\|_{L^\infty(0, t; X)}.$$

Hence

$$(3.2) \quad \|G(u) - G(v)\|_{L^1(0, t; X)} \leq \int_0^t \gamma(s) \|u - v\|_{L^\infty(0, s; X)} ds,$$

with

$$(3.3) \quad \gamma(s) = |r(0)| + \text{var}(r : [0, s]).$$

Since $r \in BV([0, T]; \mathbb{R})$ (because $a = b'$ has this property - see Proposition 1), (3.2),

(3.3) imply that G satisfies (2.1). By Proposition 1, u_λ is a strong solution of

$$(3.4) \quad \frac{du_\lambda}{dt} + A_\lambda u_\lambda \ni G(u_\lambda), \quad u_\lambda(0) = F(0).$$

One has $\lim_{\lambda \rightarrow 0} (I + \mu A_\lambda)^{-1} z = (I + \mu A)^{-1} z$ for $\mu > 0, z \in X$. Thus by Theorem 3 the u_λ converge to u in $C([0, T]; X)$ as desired. If $F' \in BV([0, T]; X)$, (1.6)((i) - (iii)) imply that

$$(3.5) \quad \begin{cases} \text{var}(G(u):[0,t]) \leq C(1 + \text{var}(u:[0,t])) \\ \|G(u)(0+)\| \leq C, \quad 0 \leq t \leq T, \end{cases}$$

where C is a constant depending on $F(0)$, $F'(0^+)$, $\text{var}(F':[0,T])$, $r(0+)$, and $\text{var}(r:[0,T])$. Thus Theorem 2 implies that the solution u is Lipschitz continuous on $[0,T]$ if $u(0) = F(0) \in D(A)$. If X is reflexive, u is a strong solution of (1.1) on $[0,T]$, and by Proposition 1, u is a strong solution of (3.1) on $[0,T]$. This completes the proof of Theorem 4.

Observe that if (3.1) has a strong solution u on $[0,T]$ under the assumptions of Theorem 2, then it follows from Theorem 2 and Proposition 1 that $\lim_{\lambda \rightarrow 0} u_\lambda = u$ in $C([0,T];X)$. However, whether or not (3.1) has a strong solution, the solutions u_λ of (3.1) $_\lambda$ converge to a limit u as $\lambda \rightarrow 0$. We adapt the point of view that this limit is a generalized solution of (3.1):

Definition. Let the assumptions of Theorem 4 be satisfied. Then $u = \lim_{\lambda \rightarrow 0} u_\lambda$ in $C([0,T];X)$ is the generalized solution of (3.1) on $[0,T]$.

The generalized solution is a continuous function of the data b, A, F via Theorem 3. The dependence of the solution on b, F can be estimated explicitly by the method of Remark 2.14. We present below the simpler estimate which results from varying only F .

Theorem 5. Let b satisfy the assumptions of Theorem 4 and $F, \hat{F} \in W^{1,1}(0,T;X)$, $F(0), \hat{F}(0) \in D(A)$. Let $u, \hat{u} \in C([0,T];D(A))$ be the generalized solutions on $[0,T]$ of the equations $u + b * Au \ni F$ and $\hat{u} + b * A\hat{u} \ni \hat{F}$ respectively. Then

$$\|u(t) - \hat{u}(t)\| \leq e(t) + \int_0^t \exp\left(\int_s^t \gamma(\tau) d\tau\right) e(s) ds \quad (0 \leq t \leq T),$$

where

$$e(t) = c_1 \|F(0) - \hat{F}(0)\| + c_2 \int_0^t \|F'(s) - \hat{F}'(s)\| ds,$$

$$c_1 = 1 + \|r\|_{L^1(0,T;\mathbb{R})}, \quad c_2 = 1 + \|r\|_{L^\infty(0,T;\mathbb{R})},$$

$$\gamma(s) = |r(0+)| + \text{var}(r:[0,s]),$$

and r is determined by $r + b' * r = -b'$.

Theorem 5 is proved by substituting into (2.15), (2.16) and estimating. Here G, \hat{G} are given by (1.6)(i) with $f = F', x = F(0)$ and $f = \hat{F}', x = \hat{F}(0)$ respectively; γ is determined from (3.2), (3.3). Theorem 5 implies that the mapping: $W^{1,1}(0,T;X) \ni F \rightarrow$ the generalized solution u of (3.1) on $[0,T]$ is Lipschitz continuous on the set of $F \in W^{1,1}(0,T;X)$ satisfying $F(0) \in \overline{D(A)}$. Thus if X is reflexive, the generalized solution of (3.1) may be regarded as the unique limit of strong solutions.

4. Connections with Other Research and Generalizations. Concerning the existence and uniqueness of solutions of the Volterra equation (3.1), Theorem 4 generalizes results of Barbu [1], Londen [13] and MacCamy [15], all for the case $X = H$ a real Hilbert space, and $Au = \partial\varphi(u)$, where $\partial\varphi$ denotes the subdifferential of a function $\varphi : H \rightarrow (-\infty, \infty]$ which is convex, l.s.c., and proper, and of Gripenberg [11; Theorem 1] for the case in which $X=H$ and A is a maximal monotone operator on H . Barbu [2] and Gripenberg [11; Theorem 2] consider certain cases when the kernel b is operator-valued. Our assumptions concerning the kernel b and the function F are closest to those of [11] and [13]. In Barbu [1] the kernel b is assumed to be of positive type which, while less general in some respects than the kernels of [11], [13] and this paper does permit the possibility that $b(0+) = +\infty$. Londen and Staffans [14] also study (3.1) in the case $X = H$, $Au = \partial\varphi(u)$, and they relax the assumption of [11] and [13] that $b' \in BV[0,T]$; they require instead that b' satisfies a frequency domain condition which holds automatically if $b' \in BV[0,T]$. Theorem 5 has not been considered by any of these authors.

We should mention how the case in which $A = \partial\varphi$ is treated in our context. From [6, Thm. 3.6] it follows at once that in this case the solution u of (3.1) provided by Theorem 4 satisfies $u' \in L^2(0,T;H)$ if only $F(0) \in D(\varphi)$ and $F' \in L^2(0,T;H)$. If $F(0) \in \overline{D(\varphi)}$ and $F' \in L^2(0,T;H)$, then we have $tu' \in L^2(0,T;H)$. Moreover, $b' \in BV([0,T];H)$ can be relaxed to (for example) the assumption that $b \in AC([0,T];H)$ and $b' \in BV([0,T_0];H)$ for some $T_0 > 0$ by use of a continuation argument as in [13].

Theorem 4 can be used to strengthen a result of Clément and Nohel [7; Theorem 5] concerning the positivity of solutions of the Volterra equation (3.1).

If $A(t)$ is a m -accretive operator for almost all $t \in [0,T]$, $\overline{D(A(t))} = D$ is constant a.e. and $g \in L^1(0,T;X)$, it is known [10] that the evolution problem

$$(4.1) \quad \begin{cases} \frac{dv}{dt} + A(t)v \ni g(t) \\ u(0) = x \end{cases} \quad (0 \leq t \leq T),$$

has a "solution" $v \in C([0,T];D)$ if $x \in D$, provided only that either

$$(4.2) \quad \left\{ \begin{array}{l} \text{There exists a Banach space } Y, h \in L^1(0, T; Y), \text{ and a continuous} \\ \text{function } L : [0, \infty) \rightarrow [0, \infty) \text{ such that} \\ \|A_\lambda(t)x - A_\lambda(s)x\|_X \leq \|h(t) - h(s)\|_Y L(\|x\|_X) \\ \text{for all } \lambda > 0, x \in X \text{ and almost all } s, t \in [0, T], \end{array} \right.$$

or

$$(4.3) \quad \left\{ \begin{array}{l} \text{There exist } h, L \text{ as in (4.2), } h \in BV([0, T]; Y) \text{ such that} \\ \|A_\lambda(t)x - A_\lambda(s)x\|_X \leq \|h(t) - h(s)\|_Y L(\|x\|_X) (1 + \|A_\lambda(s)x\|) \\ \text{for } \lambda > 0, x \in X \text{ and almost all } s, t \in [0, T], \end{array} \right.$$

where $A_\lambda(t) = \lambda^{-1}(I - (I + \lambda A(t))^{-1})$. Moreover, if $v = H(g)$ is the solution of (4.1), then

$$(4.4) \quad \|H(g)(t) - H(\hat{g})(t)\| \leq \int_0^t \|g(s) - \hat{g}(s)\| ds \quad (0 \leq t \leq T),$$

where $g, \hat{g} \in L^1(0, T; X)$. Since the property (4.4) of H was all we needed to find fixed points of the map $K = HG$ in Section 2, we can therefore solve the more general delay equation

$$\frac{du}{dt} + A(t)u \ni G(u), \quad u(0) = x \quad (0 \leq t \leq T)$$

where $G(u)$ satisfies (2.1), (2.2), and also the Volterra equation

$$u + b * A(t)u \ni F \quad (0 \leq t \leq T),$$

as in Sections 2 and 3. The notion of "solution" of (4.1) is more complex than if A is independent of t , and the technical details concerning (4.1) are otherwise too complicated to warrant more precision here. Thus we remark only that (4.2) or (4.3) suffice for a good existence theory and, given knowledge of (4.1), the proofs are the same. See [10] and [17] concerning (4.1). In particular, one easily generalizes the results of Gripenberg [11, Theorem 2].

Another type of generalization arises if we relax the assumptions concerning G in Theorem 1. For example let G be only "locally Lipschitz" in the following sense:

$$(4.5) \quad \begin{cases} \text{Let } x \in \overline{D(A)}, u_0(t) = x, 0 \leq t \leq T, R > 0, \\ M = \{u \in C([0, T]; \overline{D(A)}) : \|u - u_0\|_{L^\infty(0, T; X)} < R, \text{ and } \gamma \in L^1(0, T; \mathbb{R}^+), \\ \text{Assume that } G : M \rightarrow L^1(0, T; X), \text{ satisfies} \\ \|G(u) - G(v)\|_{L^1(0, t; X)} \leq \int_0^t \gamma(s) \|u - v\|_{L^\infty(0, s; X)} ds \text{ for } u, v \in M. \end{cases}$$

Then we can prove the following "local theorem" for the delay equation (1.1).

Theorem 6. Let (4.5) be satisfied. Then there is a T_0 , $0 < T_0 \leq T$ and a (unique) $u \in M$ such that

$$(4.6) \quad \frac{du}{dt} + Au \ni G(u), u(0) = x, \quad 0 \leq t \leq T_0.$$

Proof: Let $w_0 \in C([0, T]; \overline{D(A)})$ be the solution of $w' + Aw \ni G(u_0)$, $w(0) = x$. Choose $T_0 > 0$ such that

$$(4.7) \quad \begin{cases} \|w_0(t) - x\| \leq R/2 & (0 \leq t \leq T_0) \\ \int_0^{T_0} \gamma(s) ds \leq 1/2. \end{cases}$$

Let $v \in M$ and u be the solution of

$$\frac{du}{dt} + Au \ni G(v), \quad u(0) = x.$$

Then using (4.5), (4.7) one has

$$\begin{aligned} \|u(t) - x\| &\leq \|u(t) - w_0(t)\| + \|w_0(t) - x\| \\ &\leq \int_0^t \|G(v)(s) - G(u_0)(s)\| ds + R/2 \\ &\leq R \int_0^t \gamma(s) ds + \frac{R}{2} \leq R, \quad (0 \leq t \leq T_0). \end{aligned}$$

The solution operator $v \mapsto HG(v) = u$ thus maps the set M into

$\{u \in C([0, T]; \overline{D(A)}) : \|u(t) - u_0(t)\| \leq R \text{ for } 0 \leq t \leq T_0\}$. Modify this mapping by setting

$$K_{T_0}(v) = \begin{cases} HG(v)(t) & \text{if } 0 \leq t \leq T_0 \\ HG(v)(T_0) & \text{if } T_0 < t \leq T. \end{cases}$$

M is now invariant under K_{T_0} and

$$\|K_{T_0}(u) - K_{T_0}(v)\|_{L^\infty(0,t;X)} \leq \int_0^t \gamma(s) \|u - v\|_{L^\infty(0,s;X)} ds \quad (u, v \in M).$$

Therefore, K_{T_0} has a unique fixed point u which is a solution of (4.6) on $[0, T_0]$.

This completes the proof of Theorem 6.

Finally, if assumption (2.1) is relaxed to

$$(4.8) \quad \|G(u) - G(v)\|_{L^1(0,T;X)} \leq M \|u - v\|_{L^\infty(0,T;X)},$$

so that $G(u)(t)$ can also depend on the values $u(\tau)$ for $\tau > t$ (which (2.1) does not allow), then the technique of Theorem 1 shows that equation (1.1) with G replaced by εG has a unique solution whenever $|\varepsilon| M < 1$.

We also wish to point out that the method developed in Sections 2 and 3 can be used to study the nonconvolution Volterra equation

$$(4.9) \quad u(t) + \int_0^t b(t,s)Au(s)ds \ni F(t) \quad (0 \leq t \leq T),$$

where A is m -accretive on X and $F \in W^{1,1}([0,T];X)$. Concerning b we assume that it is defined on the region $T = \{(t,s) : 0 \leq s \leq t \leq T\}$, that $b(t,s)$ is as smooth as required for the calculations which follow, and that $b(t,t) > 0$ ($0 \leq t \leq T$).

Differentiating (4.9) one obtains

$$(4.10) \quad \frac{du}{dt}(t) + b(t,t)Au(t) + \int_0^t \frac{\partial b}{\partial t}(t,s)Au(s)ds \ni F'(t); u(0) = F(0).$$

Putting $\varphi(t) = b(t,t) > 0$, $\tau = \phi(t) = \int_0^t \varphi(s)ds$ ($0 \leq t \leq T$), $\psi(\tau) = \varphi(\phi^{-1}(\tau))^{-1}F'(\phi^{-1}(\tau))$

($0 \leq \tau \leq \phi(T)$), and defining $v(\tau) = u(\phi^{-1}(\tau))$, $c(\tau,\sigma) = b(\phi^{-1}(\tau), \phi^{-1}(\sigma))$, an elementary calculation shows that (4.10) is transformed to the equivalent initial value problem

$$(4.11) \quad \begin{cases} \frac{dv}{d\tau} + Av(\tau) + \int_0^\tau \frac{\partial c}{\partial \tau}(\tau,\sigma) \frac{Av(\sigma)}{c(\sigma,\sigma)} d\sigma \ni \psi(\tau) \\ v(0) = x = F(0). \end{cases} \quad (0 \leq \tau \leq \phi(T)),$$

Let $k(\tau,\sigma) = \frac{\partial c}{\partial \tau}(\tau,\sigma) / c(\sigma,\sigma)$, and define the associated resolvent kernel $r(\tau,\sigma)$ by the

equation ([17; Ch. IV]):

$$(4.12) \quad r(\tau, \sigma) + \int_{\sigma}^{\tau} k(\tau, \xi) r(\xi, \sigma) d\xi = -k(\tau, \sigma) \quad (0 \leq \sigma \leq \tau \leq \phi(T)) .$$

A calculation analogous to that of Proposition 1 shows that the problem (4.11) is (under suitable assumptions) equivalent to the initial value problem

$$(4.13) \quad \frac{dv}{d\tau} + Av = G(v) \quad (0 \leq \tau \leq \phi(T); v(0) = x) ,$$

where

$$(4.14) \quad \begin{cases} G(v)(\tau) = \psi(\tau) + \int_0^{\tau} r(\tau, \sigma) \psi(\sigma) d\sigma - r(\tau, \tau) v(\tau) \\ \quad + r(\tau, 0)x + \int_0^{\tau} v(\tau - \sigma) d_{\sigma} r(\tau, \sigma) \end{cases} \quad (0 \leq \tau \leq \phi(T)) .$$

The Stieltje's integral in (4.14) is well defined if $r(\tau, \sigma)$ is of bounded variation with respect to σ on $0 \leq \sigma \leq \tau$, uniformly in τ on $0 \leq \tau \leq \phi(T)$. Under this assumption it is clear that G defined in (4.14) satisfies the estimate (3.2) with $\gamma(s) = |r(s, s)| + \sup_{0 \leq \tau \leq \phi(T)} \text{var}(r(\tau, \sigma) : 0 \leq \sigma \leq \tau)$. Thus one may apply the theory developed in Section 2 and arrive at analogues of Theorems 4 and 5 for the nonconvolution equation (4.9). We shall not pursue this this topic further.

Finally, we remark that if $X = \mathbb{R}$ and A is a nondecreasing (continuous) function from \mathbb{R} to \mathbb{R} in (3.1), and if $F \in AC([0, T])$, J. J. Levin [12; Theorem 1'] has obtained by a different method a result similar to the one to which our Theorem 4 reduces for this case.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 1765	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN ABSTRACT FUNCTIONAL DIFFERENTIAL EQUATION AND A RELATED NONLINEAR VOLTERRA EQUATION		5. TYPE OF REPORT & PERIOD COVERED Summary Report - no specific reporting period
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M. G. Crandall and J. A. Nohel		8. CONTRACT OR GRANT NUMBER(s) DAAG29-77-G-0004 DAAG29-75-C-0024 MCS75-21868
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mathematics Research Center, University of 610 Walnut Street Wisconsin Madison, Wisconsin 53706		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1 (Applied Analysis)
11. CONTROLLING OFFICE NAME AND ADDRESS See Item 18 below.		12. REPORT DATE July 1977
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES U. S. Army Research Office National Science Foundation P. O. Box 12211 Washington, D. C. Research Triangle Park 20550 North Carolina 27709		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) nonlinear abstract functional differential equations nonlinear abstract Volterra equations evolution equations m-accretive operators continuous dependence on data regularity		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) We study the existence, uniqueness, regularity and dependence upon data of solutions of the abstract functional differential equation (1) $\frac{du}{dt} + Au \ni G(u) \quad (0 \leq t \leq T), u(0) = x,$ where $T > 0$ is arbitrary, A is a given m-accretive operator in a real Banach space X , and $G : C([0, T]; \overline{D(A)}) \rightarrow L^1(0, T; X)$ is a given mapping. This		

20. ABSTRACT (cont'd.)

study provides simple proofs of generalizations of results by several authors concerning the nonlinear Volterra equation

$$(2) \quad u(t) + b * Au(t) = F(t) \quad (0 \leq t \leq T),$$

for the case in which X is a real Hilbert space. In (2) the kernel b is real, absolutely continuous on $[0, T]$, $b * g(t) = \int_0^t b(t-s)g(s)ds$, and $F \in W^{1,1}(0, T; X)$.